

# *The Alarming Phenomenon of Particle Creation in the Early Universe*

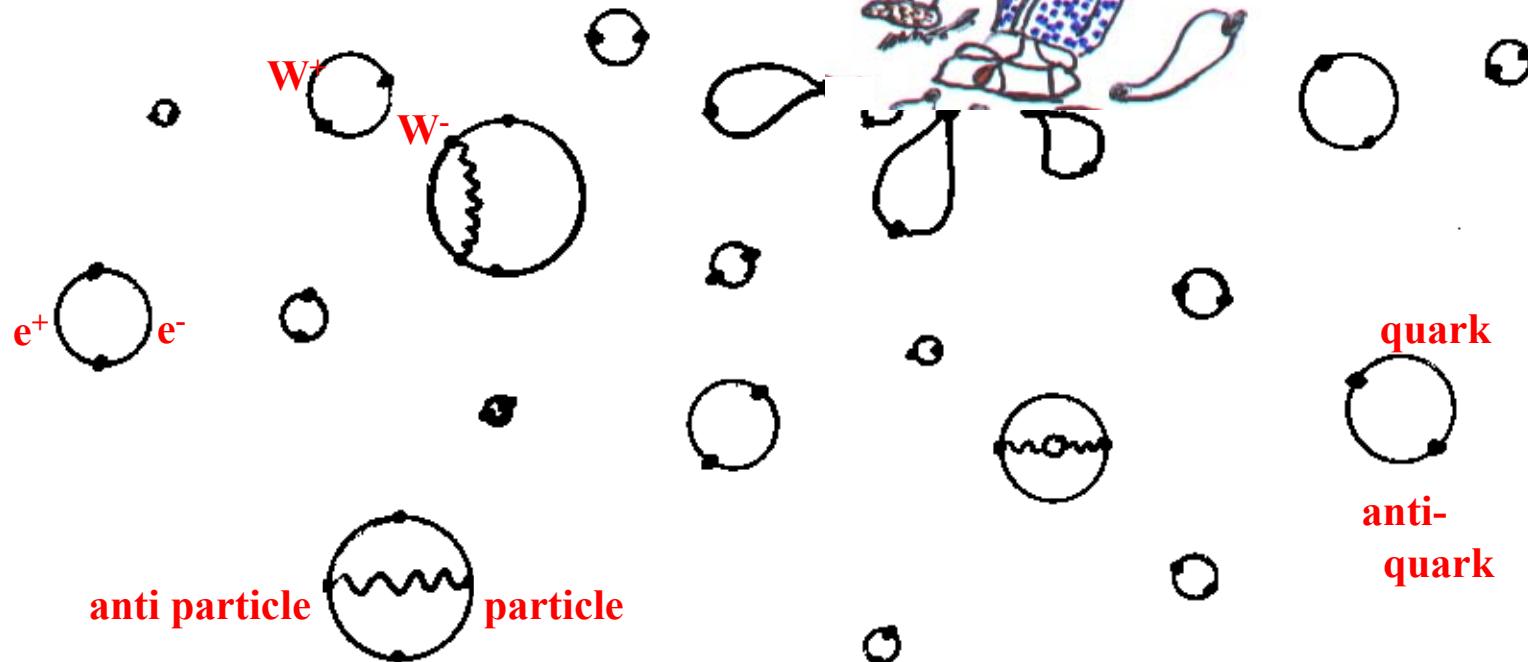


COSMO'01  
*Rovaniemi*  
*(land of many vowels)*

Rocky Kolb  
*Fermilab*  
*Chicago*

# *The Vacuum*

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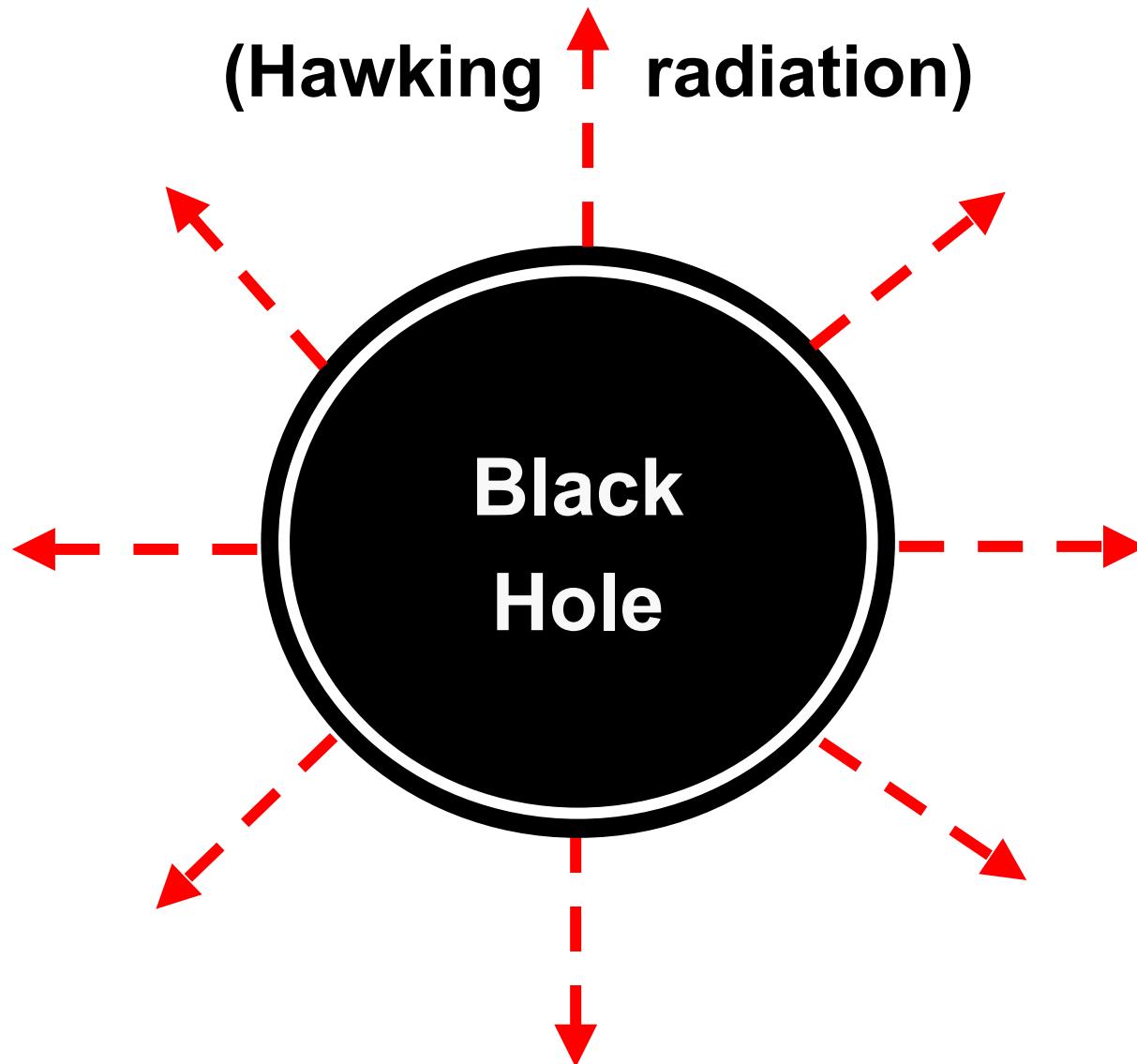


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# *Quantum Uncertainty*

# Gravity disturbs the vacuum

Strong gravitational field → particle production



# An early particle cosmologist



**In mid-1930s, Schrödinger turned to  
cosmo issues, influenced by Eddington & Lemaitre**

1938-1939: Graz → Vatican → Gent, Belgium → Dublin

# The proper vibrations of the expanding universe

Erwin Schrödinger

*Physica* **6**, 899 (1939)

## Introduction:

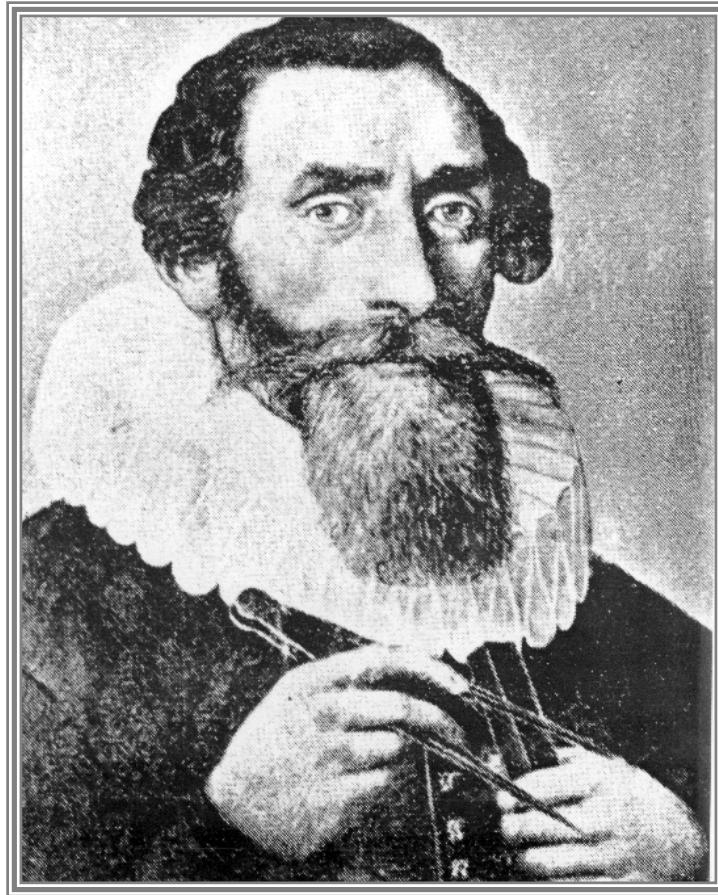
“... proper vibrations [positive and negative frequency modes] cannot be rigorously separated in the expanding universe.

... this is a phenomenon of outstanding importance [wimpzillas!]. With particles it would mean production or annihilation of matter, merely by expansion,... Alarmed by these prospects, I have examined the matter in more detail.”

## Conclusion:

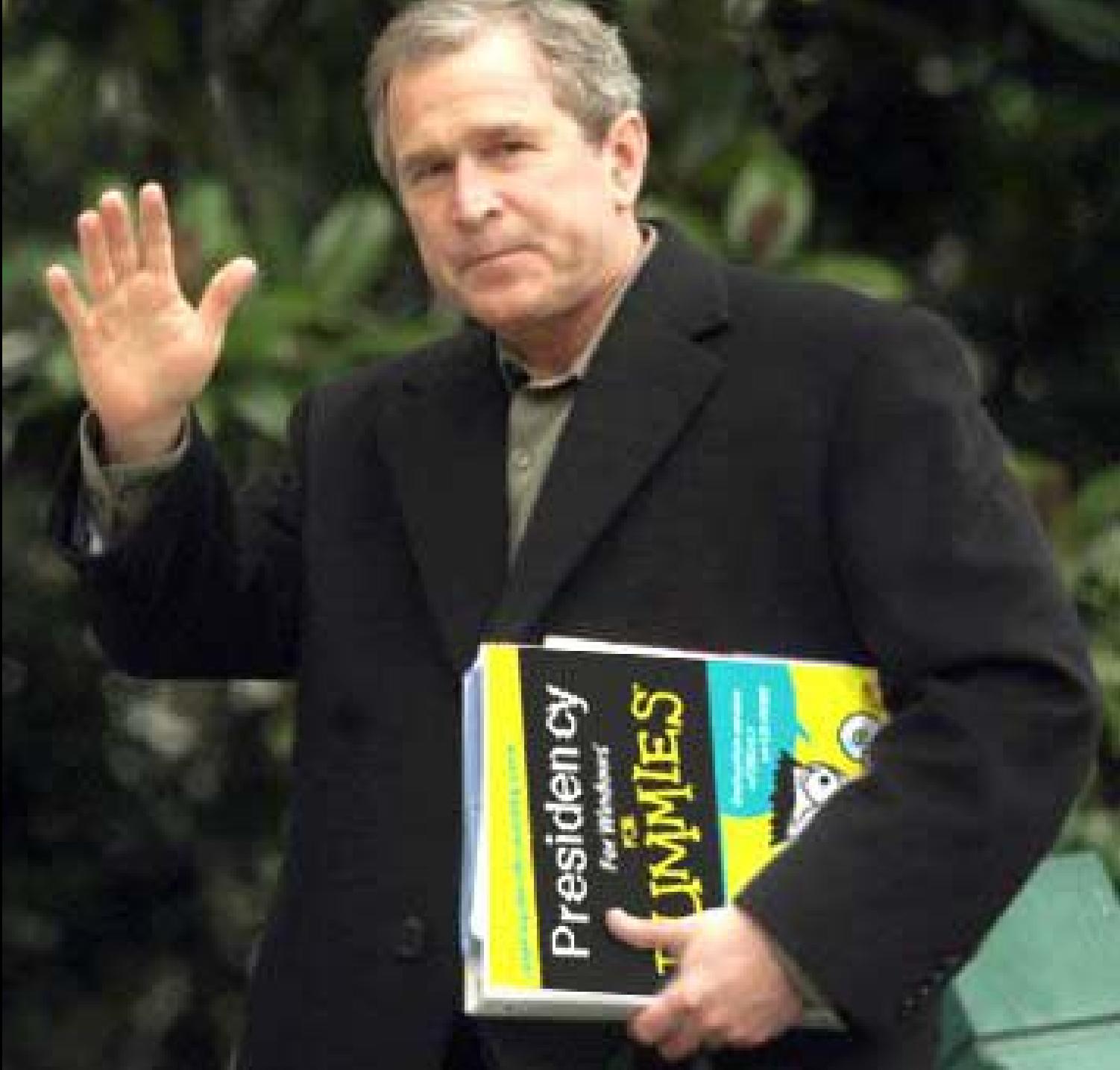
“... There will be a mutual adulteration of positive and negative frequency terms in the course of time, giving rise to ... the ‘alarming phenomenon’...”

# An even earlier Graz cosmologist



“When the storms rage around us, and the state is threatened by shipwreck, we can do nothing more noble than to lower the anchor of our peaceful studies in the ground of eternity.” - *J. Kepler*

1600-1630: Graz → Prague → Linz → Sagan → Ratisbon



# ***Expanding universe*** → ***particle creation***

(Arnowit, Birrell, Bunch, Davies, Deser, Ford, Fulling, Grib, Hu, Kofman, Mostepanenko, Page, Parker, Starobinski, Unruh, Vilenkin, Wald, Zel'dovich,...)

**first application:** { **density perturbations from inflation**  
**gravitational waves from inflation**

(Guth & Pi; Starobinski; Bardeen, Steinhardt, & Turner; Hawking; Rubakov; Fabbi & Pollack; Allen)

# Variational formalism for quantization:

Einstein gravity ————— Inflaton field

$$S = \int d^4x \sqrt{-g} \left[ -\frac{M_{Pl}^2}{16\pi} R + \frac{1}{2} (\partial\phi)^2 - V(\phi) \right]$$

$$g_{\mu\nu}(\vec{x}, t) = g_{\mu\nu}^{FRW}(t) + \delta g_{\mu\nu}(\vec{x}, t)$$

$$\phi(\vec{x}, t) = \phi_0(t) + \delta\phi(\vec{x}, t)$$

**Scalar perturbations in terms of field  $u(\delta\phi, \delta g_{\mu\nu})$**

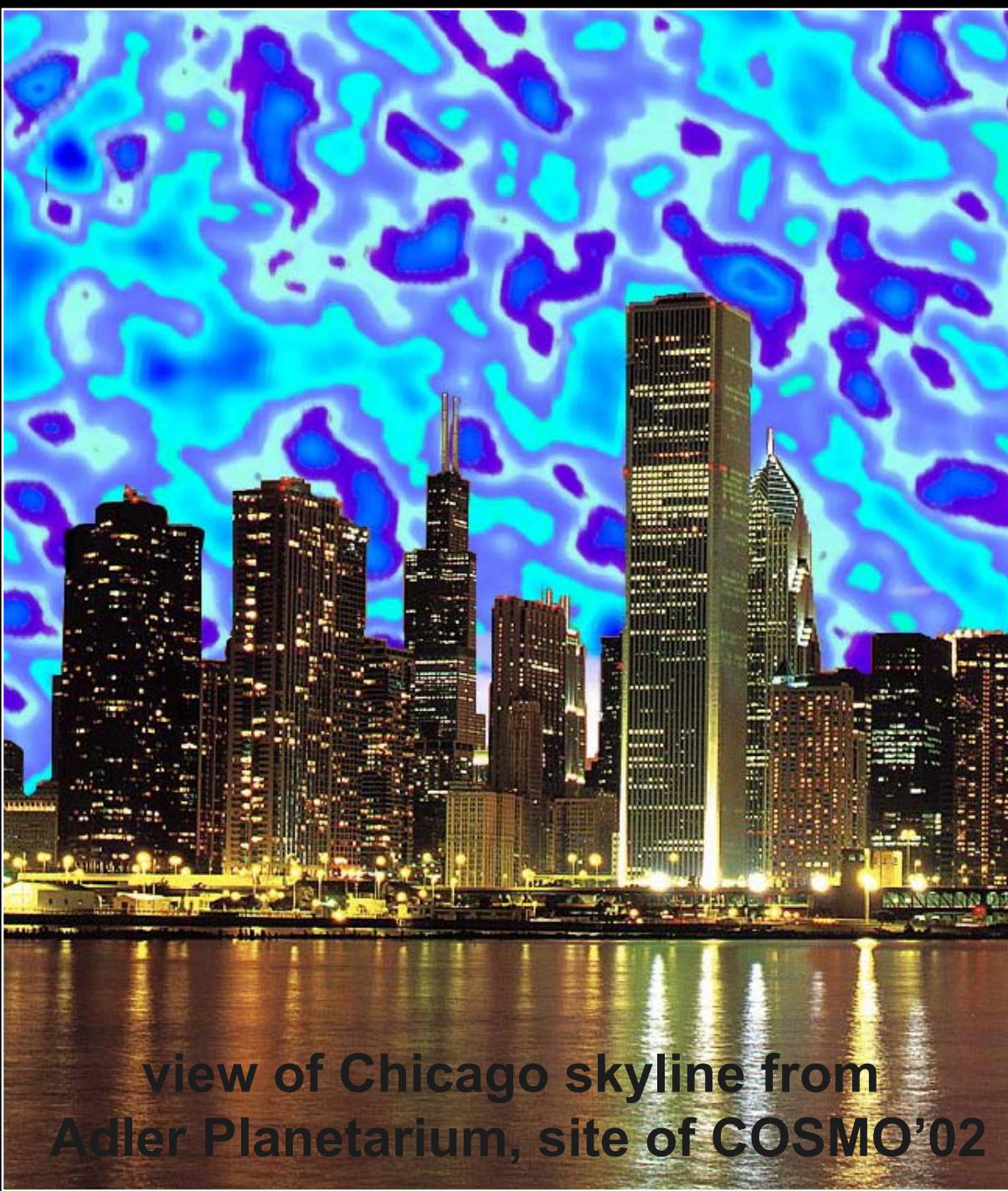
$u \propto$  curvature perturbation

$$S = \int d^4x \left( \partial_\mu u \partial^\mu u - \frac{1}{2} m_u^2 u^2 \right)$$

**Minkowski space  
(conformal time)**

$m_u^2$  changes in time

A pattern  
of  
vacuum  
quantum  
fluctuations



view of Chicago skyline from  
Adler Planetarium, site of COSMO'02

# ***Expanding universe*** → ***particle creation***

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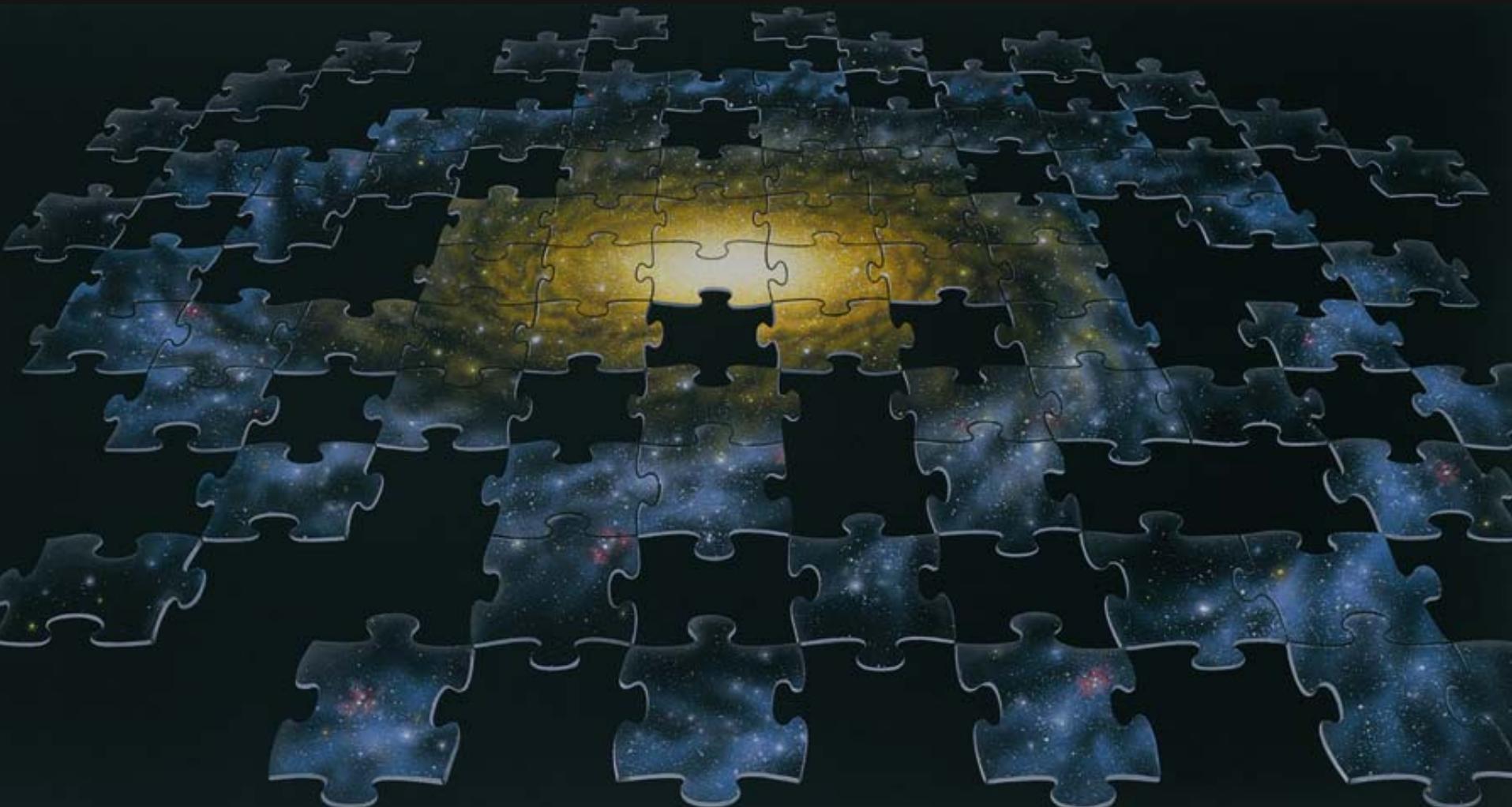
(Guth & Pi; Starobinski; Bardeen, Steinhardt, & Turner; Hawking; Rubakov; Fabbi & Pollack; Allen)

**new application:** **dark matter**

(Chung, Kolb, & Riotto; Kuzmin & Tkachev)

- require (super)massive particle “X”
- stable (or at least long lived)
- initial inflationary era followed by radiation/matter

# Missing Pieces



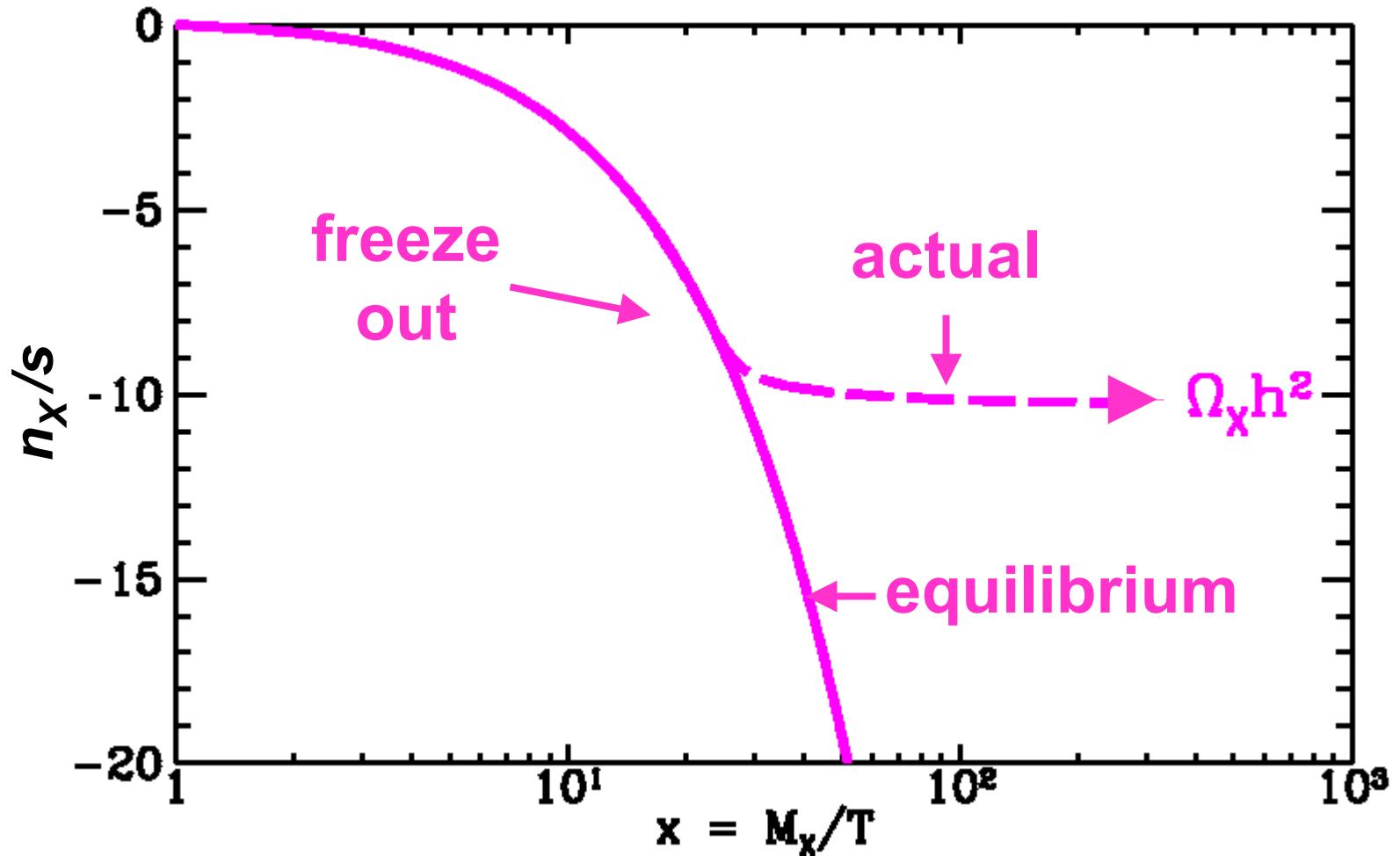
Dark Matter

Run 1339 Col 4 Field 75

Rocky I



# Cold thermal relics



$$\Omega_X \propto \sigma_A^{-1} \quad (\text{independent of mass})$$

# Thermal WIMP: interaction & mass limit

$$\Omega_X \propto \sigma_A^{-1}$$

$\sigma_A$  related to scattering cross section

$$\Omega_X \approx 1$$

$\sigma_A$  of the order of the weak scale

$$\sigma_A \leq \frac{8\pi}{m_X^2}$$

unitarity limit to the cross section

$$\Omega_X \leq 1 \Rightarrow M_X \leq 200 \text{ TeV}$$

**Thermal WIMP: interaction strength determined  
mass undetermined (but < 200 TeV)**

# *Dark Matter*

**WIMP**

or

**WIMPZILLA**



# Scalar field $X$ of mass $M_X$

## Fourier modes

$$X(\vec{x}, \eta) = \int \frac{d^3x}{(2\pi)^{3/2} a(\eta)} \left[ a_k h_k(\eta) e^{i\vec{k}\cdot\vec{x}} + a_k^+ h_k^*(\eta) e^{-i\vec{k}\cdot\vec{x}} \right]$$

## Mode equation ( $\eta$ = conformal time)

$$h_k''(\eta) + \left[ k^2 + M_X^2 a^2 + (6\xi - 1) a''/a \right] h_k(\eta) = 0$$

$$h_k''(\eta) + \omega_k^2(\eta) h_k(\eta) = 0$$

## Particle creation in nonadiabatic region

measure of nonadiabaticity  $\propto \frac{\omega'_k}{\omega_k}$     or     $\frac{\dot{H}}{H^2}$

## No-particle state in past

$$a_k^0 |0\rangle = 0 \quad h_k^0 \quad a_k^0$$

$h_k(\eta)$  adulterated as  $\omega_k(\eta)$  changes

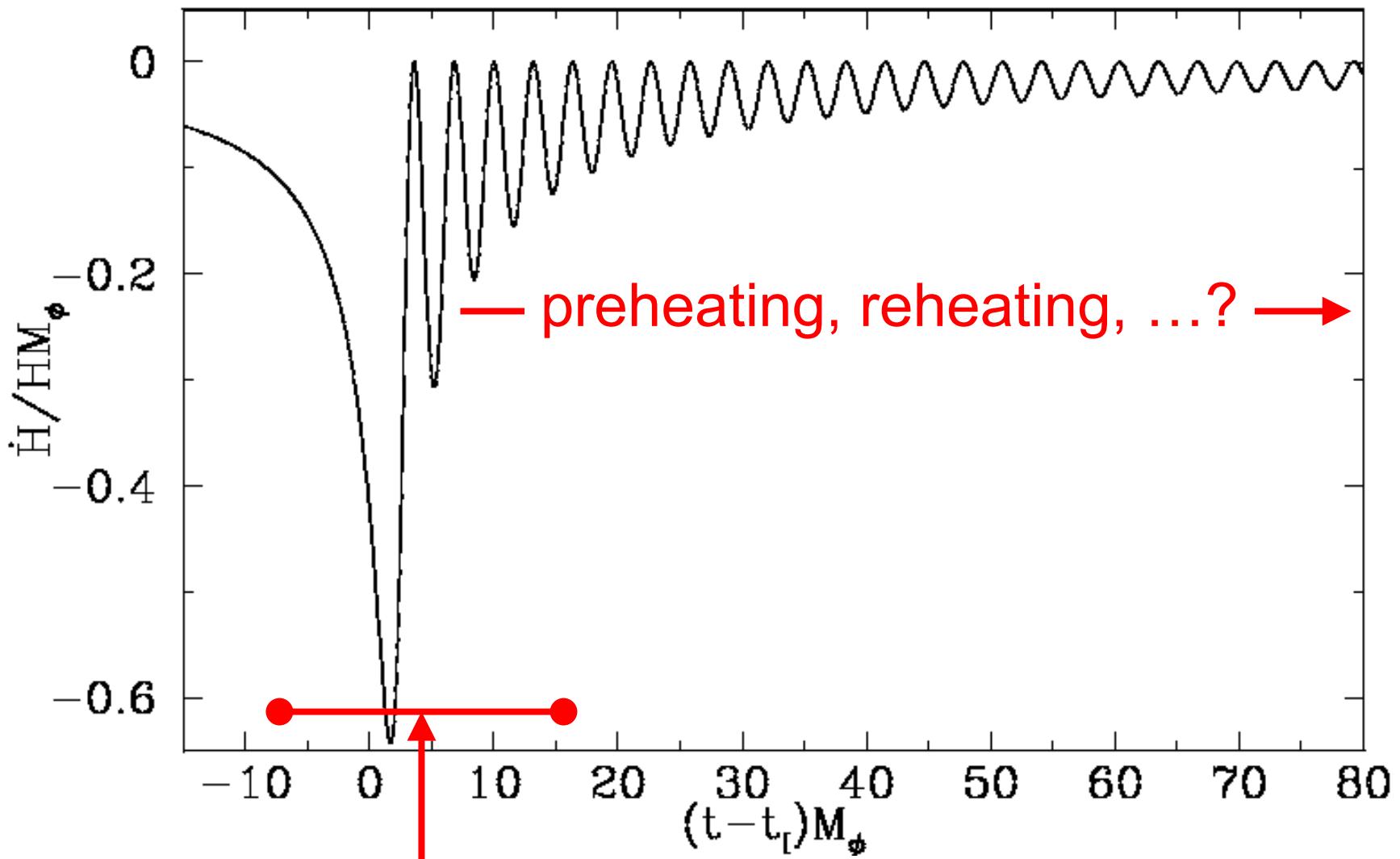
$$h_k = \alpha_k h_k^0 + \beta_k h_k^{0*}$$

$$a_k = \alpha_k a_k^0 - \beta_k a_k^{0+}$$

## Particle creation

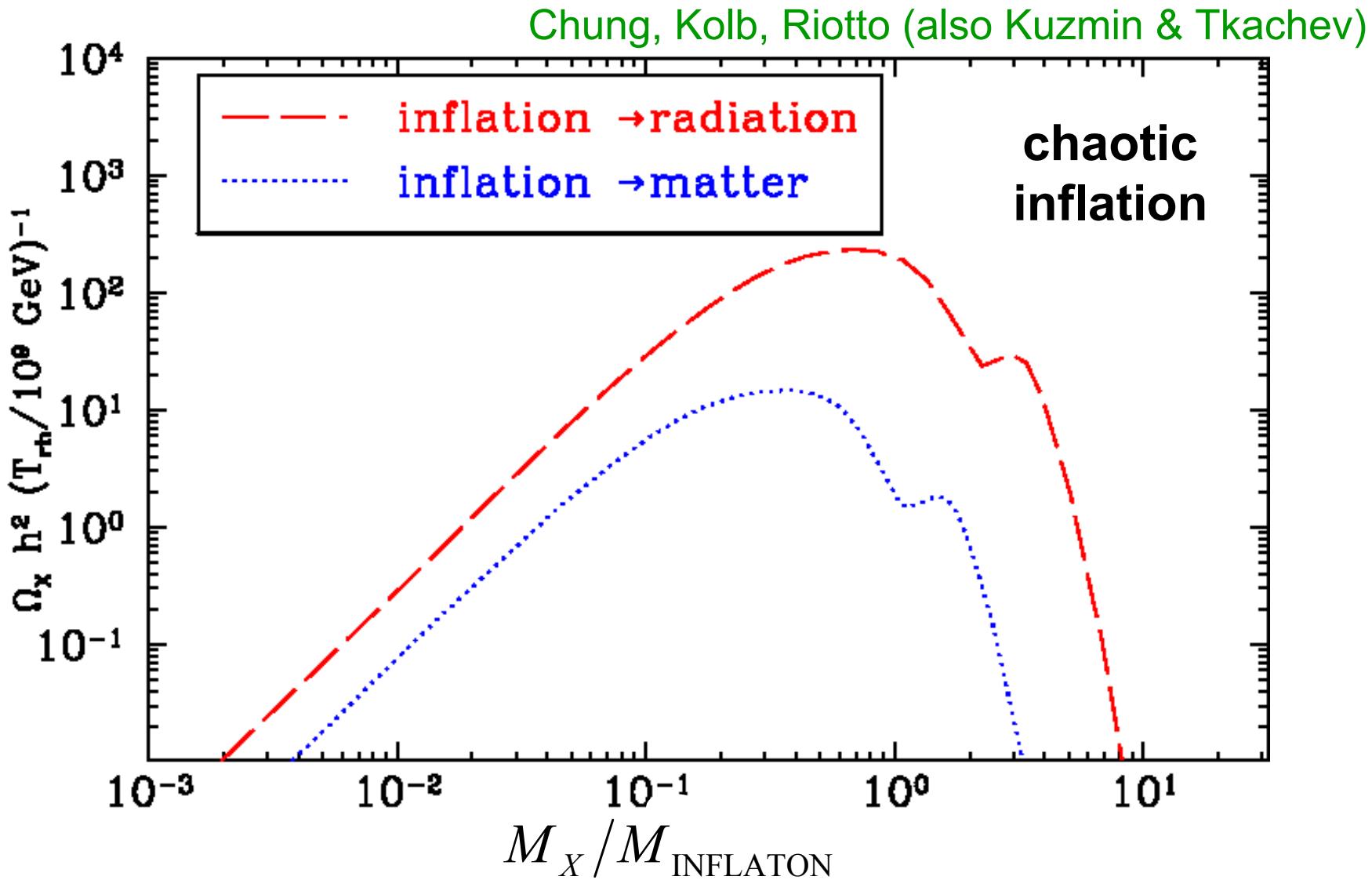
$$N_k = \langle 0 | a_k^+ a_k^- | 0 \rangle \propto |\beta_k|^2$$

# Background fields in chaotic inflation



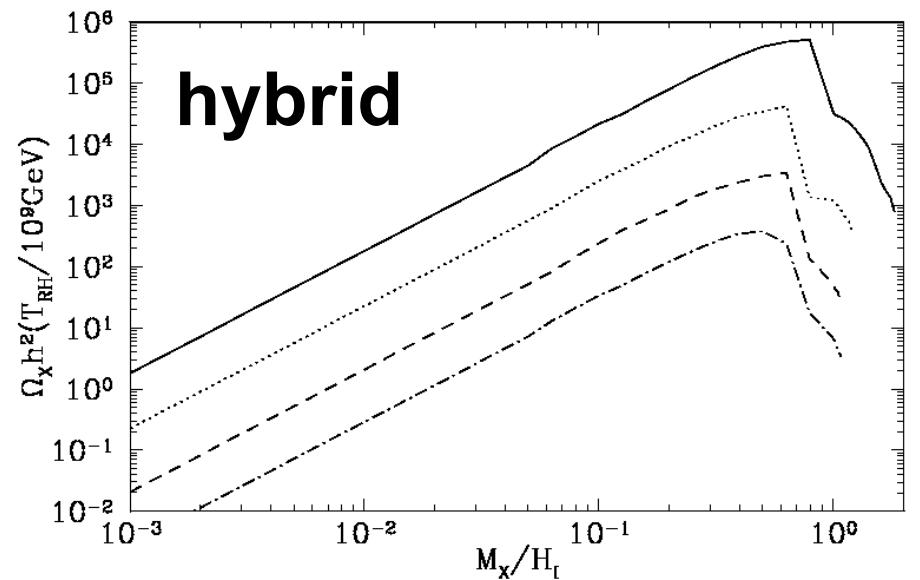
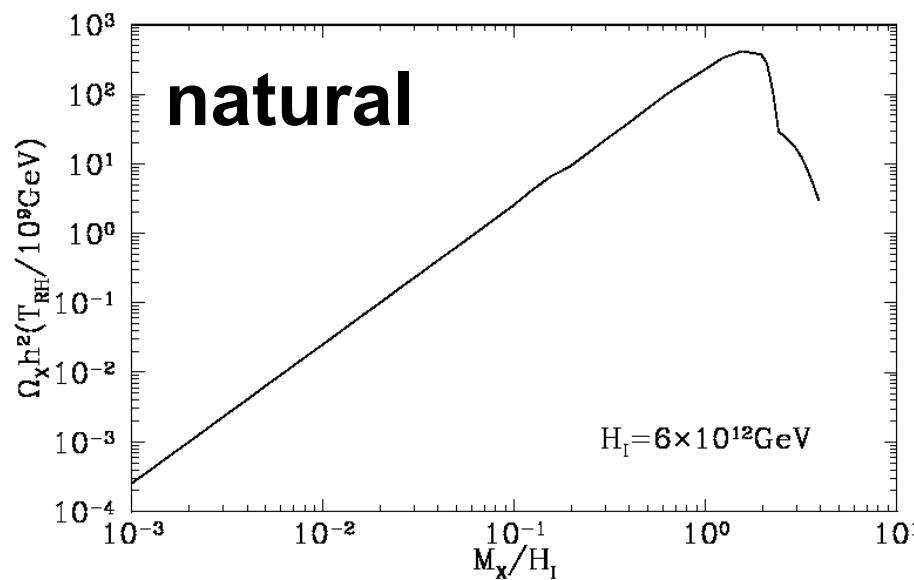
nonadiabatic region: particle creation

# WIMPZILLA production



$\Omega_X \approx 1$  for  $M_X/M_{\text{INFLATON}} \approx 1 \Rightarrow M_X \approx 10^{10}$  to  $10^{15} \text{ GeV}$

# Model Exploration



$$M_X \leq H_I \rightarrow \Omega_X h^2 \approx \left( \frac{M_X}{10^{11} \text{ GeV}} \right)^2 \left( \frac{T_{RH}}{10^9 \text{ GeV}} \right)$$

$$M_X \geq H_I \rightarrow \Omega_X h^2 \propto \exp(-M_X/H_I)$$

Chung, Crotty, Kolb, Riotto

# More Model Exploration

## Gravitational Production:

- Fermions
- Non-conformal couplings
- Small-field models
- Hybrid models
- Fat wimpzilla

Kuzmin & Tkachev

Kuzmin & Tkachev

Crotty, Chung, Kolb, Riotto

Crotty, Chung, Kolb, Riotto



## Other Mechanisms:

- Reheating
- Preheating
- Bubble collisions

Chung, Kolb, Riotto

Chung

Chung, Kolb, Riotto

# **Superheavy particles**

**Inflaton mass (in principle measurable from gravitational wave background, guess  $10^{12}$  GeV) may signal a new mass scale in nature.**

**Other particles may exist with mass comparable to the inflaton mass.**

# Long-live superheavy particles!

**In superstring models:**

Ellis, Gelmini, Lopez, & Nanopoulos

**With discrete gauge symmetries:**

Hamaguchi, Nomura, & Yanagida

**In dynamical SUSY breaking models:**

Hamaguchi, Izawa, Nomura, & Yanagida

**Brane-world mechanisms:**

Crooks, Dunn, & Frampton

**With conserved quantum numbers (possibly discrete):**

# Superheavy relic (wimpzilla)

## characteristics:

- Supermassive:  $10^9$  -  $10^{19}$  GeV ( $\sim 10^{12}$  GeV ?)
- abundance may depend only on mass
- abundance may be independent of interactions
  - sterile?
  - electrically charged?
  - strong interactions?
  - weak interactions?
- unstable (lifetime > age of the universe)?

# WIMPZILLA footprints:



**Decay:**

Ultra High Energy Cosmic Rays

**Annihilate:**

Galactic Center, Sun

**Isocurvature Perturbations:**

Structure Formation, CMB

**Direct Detection:**

Bulk, Underground Searches

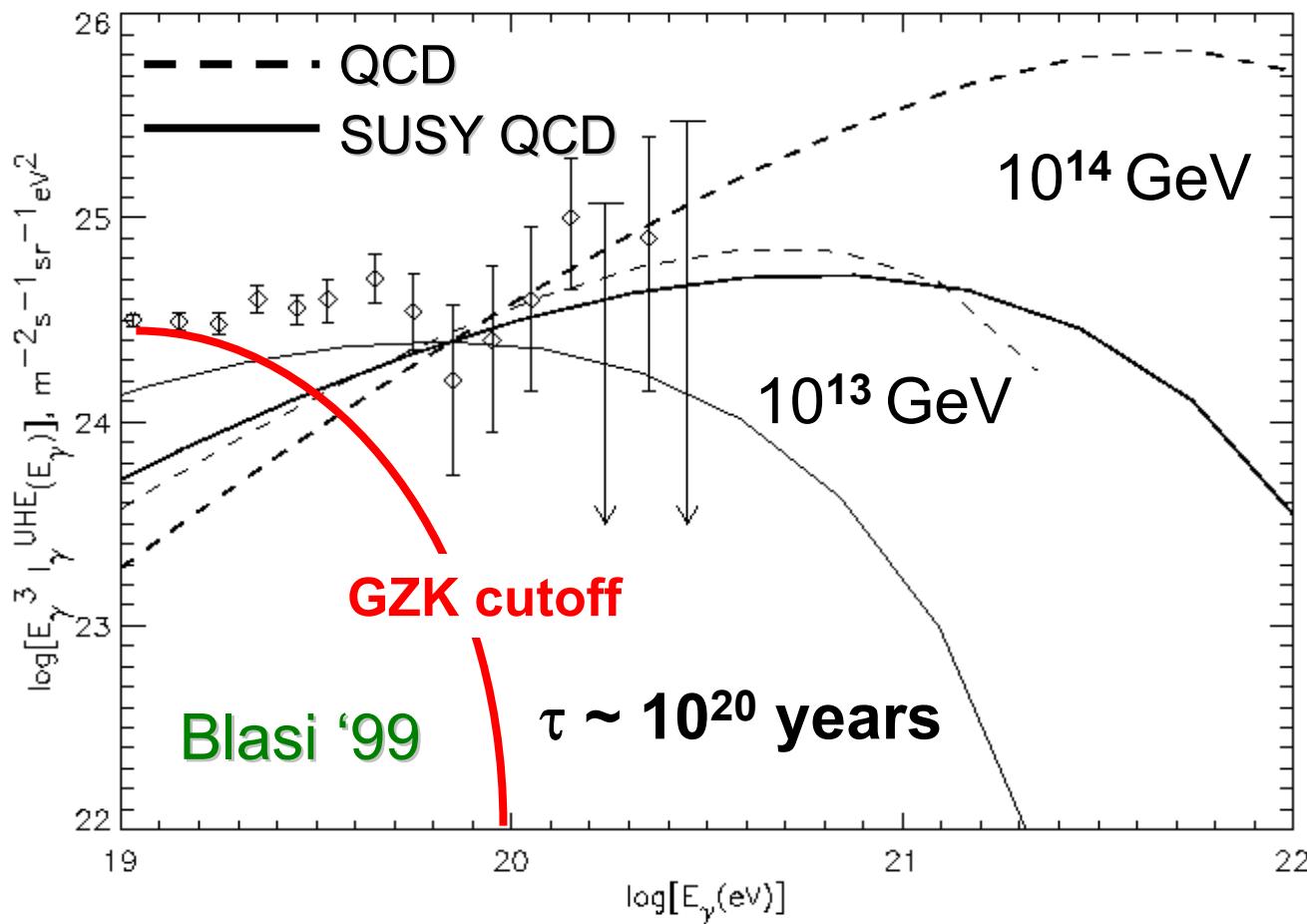
# WIMPZILLA decay

$X \longrightarrow$  UHE cosmic rays

$$10^{13} \text{ GeV} = 10^{22} \text{ eV}$$

Kuzmin & Rubakov; Birkel & Sarkar;  
Ellis, Gelmini, Lopez, Nanopoulos & Sarkar;  
Berezinsky, Kachelriess, & Vilenkin;  
Benakli, Ellis, & Nanopoulos; Berezinsky, Blasi, & Vilenkin;  
Blasi; Berezinsky & Mikhajlov;  
Dubovsky & Tinyakov; Medina-Tanco & Watson;  
Blasi & Seth; Ziaeepour; Crooks, Dunn, & Frampton

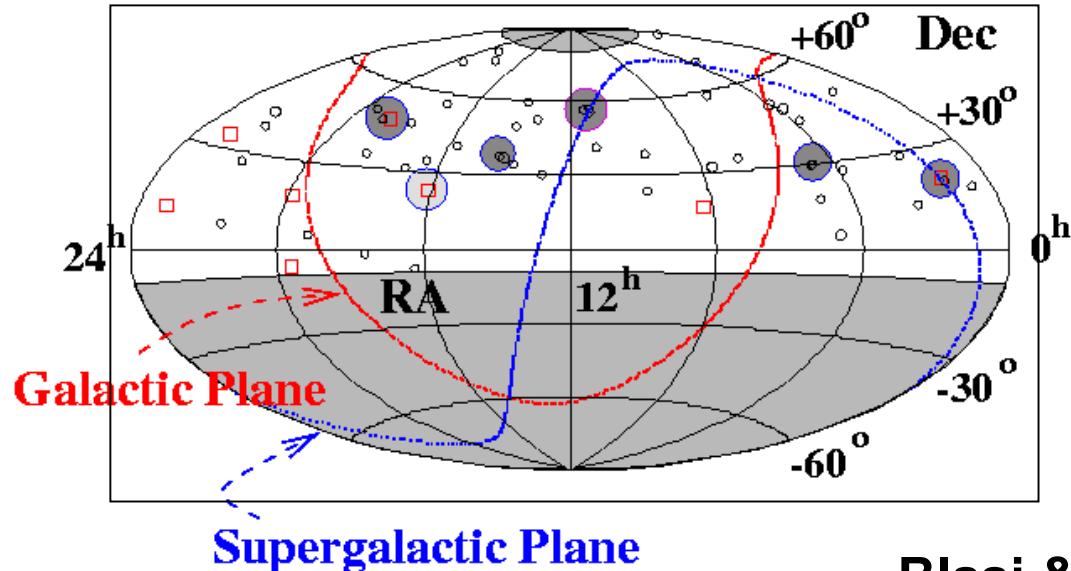
# WIMPZILLA decay



UHE cosmic rays mostly photons; characteristic spectrum;  
UHE neutrinos; lower-energy crud;  
clumping → anisotropies

# Clustering of UHE events

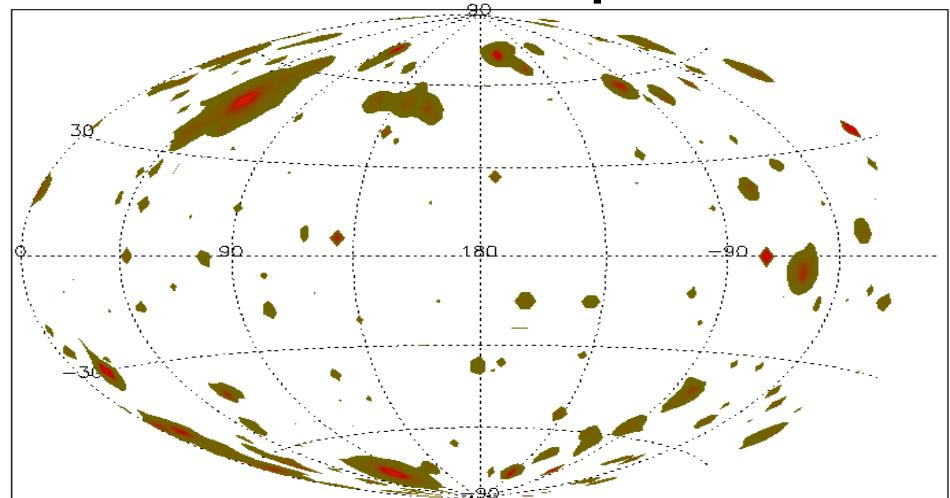
UHE cosmic rays



probability from  
isotropic distribution:  
<1%

model follows Navarro,  
Frenk, White dark matter  
distribution

Blasi & Sheth astro-ph/0006316



# WIMPZILLA annihilation

- **WIMPZILLAS collect in galactic center**

**XX → photons, antiprotons, positrons**

Bertone, Silk, Sigl      astro-ph/0011553

**XX → UHE cosmic rays**

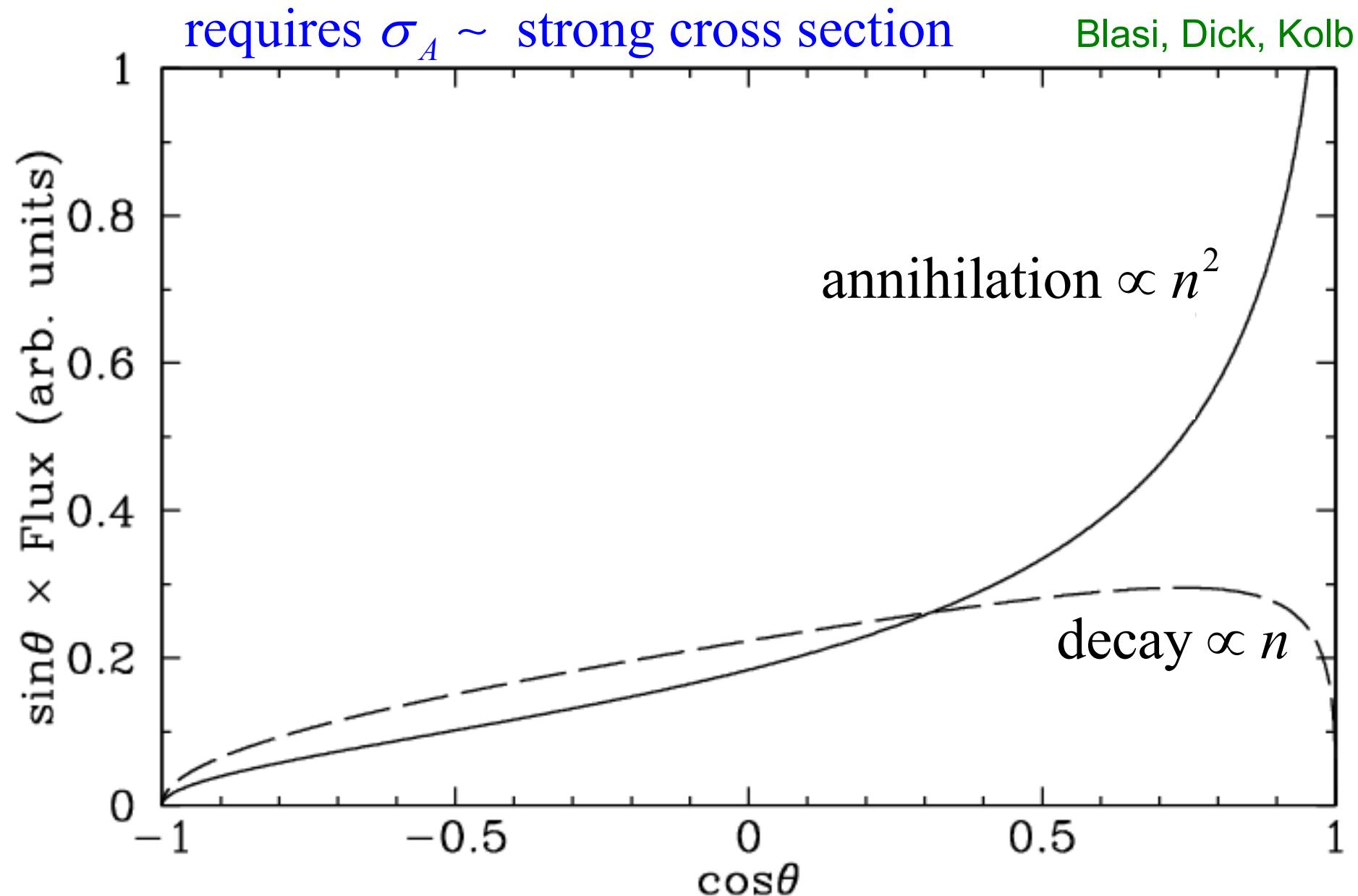
Blasi, Dick, Kolb      astro-ph/yymmnnn

- **WIMPZILLAS collect in sun**

**XX → neutrinos**

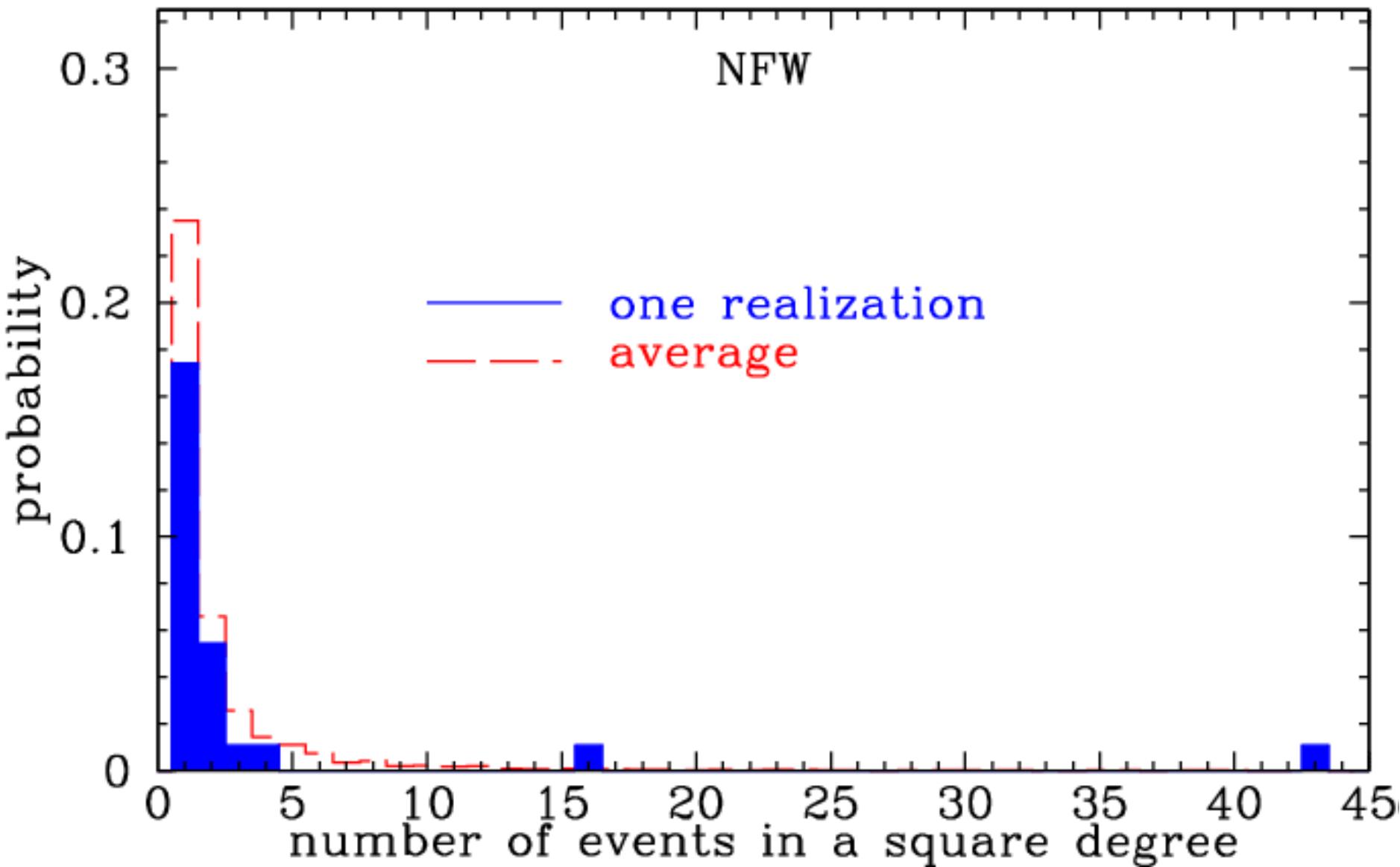
Albuquerque, Hui, Kolb      hep-ph/0009017

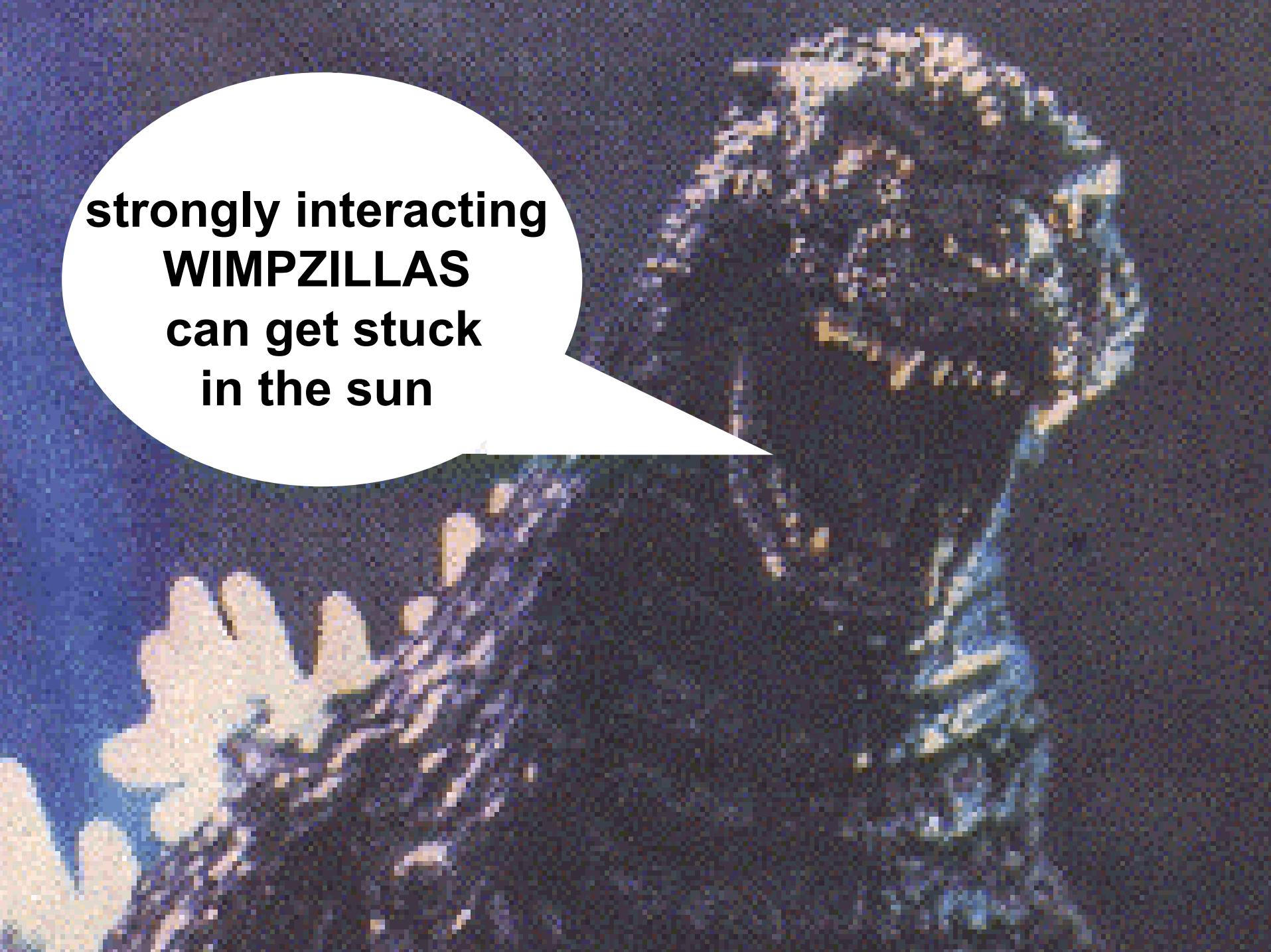
# UHE events from galactic center



# Annihilation from subclumps

Blasi, Dick, Kolb





A close-up photograph of a sunflower head, showing its characteristic yellow petals and dark central disk. The image serves as the background for the text.

**strongly interacting  
WIMPZILLAS  
can get stuck  
in the sun**

# Capture rate in the sun

Press & Spergel; Gould; ....

Wimpzilla of mass  $M = 10^{12} M_{12} \text{GeV}$

$$\rho = 0.3 \text{ GeV cm}^{-3} \quad \rightarrow \quad n = 3 \times 10^{-13} M_{12}^{-1} \text{ cm}^{-3}$$

$$v = 244 \text{ km s}^{-1} \quad \rightarrow \quad F = 6 \times 10^{-7} M_{12}^{-1} \text{ cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$$

$$A_{SUN} = 6 \times 10^{22} \text{ cm}^2 \quad \rightarrow \quad 4 \times 10^{16} M_{12}^{-1} \text{ s}^{-1} \text{ hit sun}$$

**But they gotta stick!**

# Sticking in the sun

Hit the sun:  $v = v_{escape}$

- initial kinetic energy =  $10^6 M_{12} \text{GeV}$

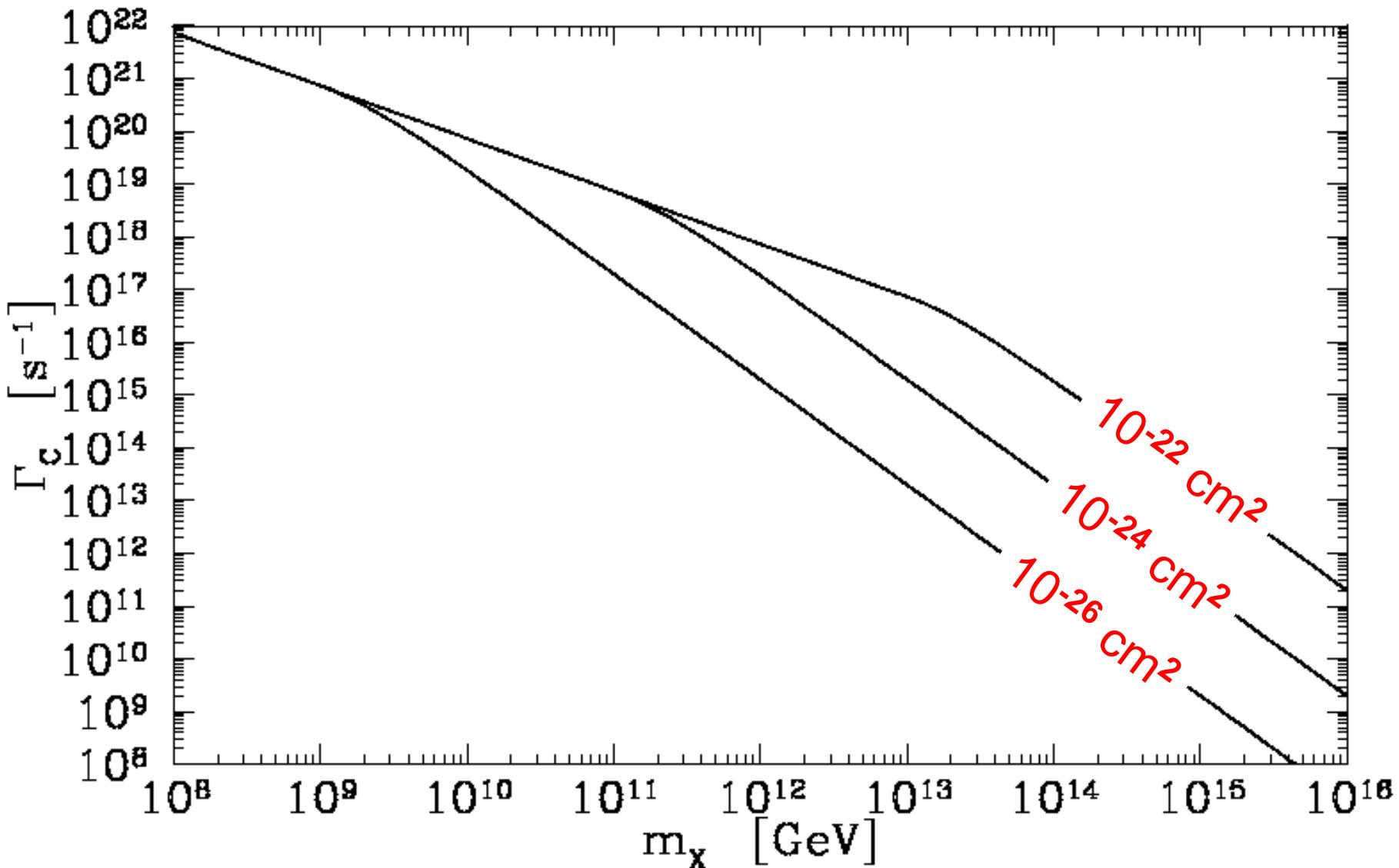
Scatter in the sun:  $\sigma = 10^{-24} \sigma_{-24} \text{cm}^2$

- # collisions =  $10^{12} \sigma_{-24}$
- energy loss =  $m_{proton} v^2$  per collision
- energy loss =  $10^6 \sigma_{-24} \text{ GeV}$  through sun

Most captured if  $\sigma_{-24}/M_{12} \geq 1$

Otherwise, capture only low-velocity tail

# Capture rate in sun



# Sinking SIMPZILLAS

Strongly interacting w/IMPZILLA = SIMPZILLA

Massive  $\rightarrow$  small velocity  $\rightarrow$  sink

Initial configuration thermally supported

$$N \approx 10^{26} \quad r \approx 50 \text{ meters}$$

Then collapse

- Self gravitating or large nucleus?
- Black hole?
- Sufficient annihilation to reach equilibrium

$$N \approx 10^{30} \quad r \approx 10^{-4} \text{ cm}$$

$$\Gamma_A = \Gamma_C$$

# Fragmentation



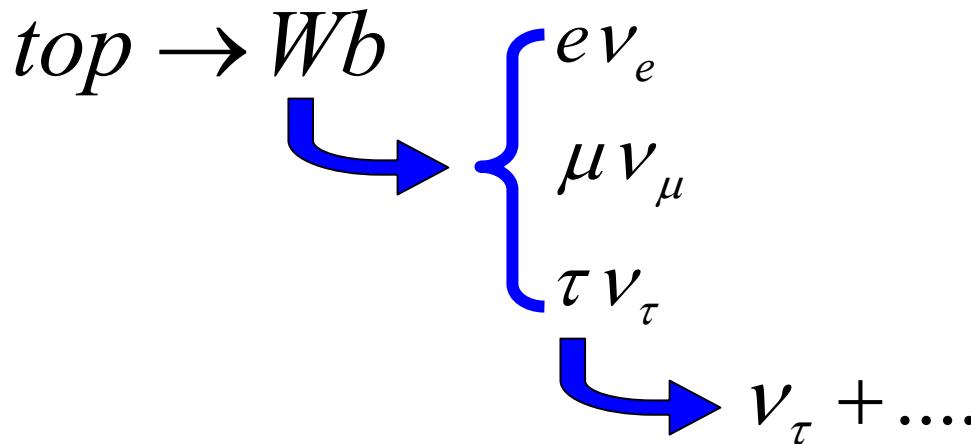
$$N_H = 7 \times 10^6 M_{12}^{1/2}$$

$$N_c = 2 \times 10^6 M_{12}^{1/2}$$

$$N_b = 1 \times 10^6 M_{12}^{1/2}$$

$$N_t = 3 \times 10^5 M_{12}^{1/2}$$

# Decay



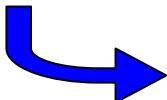
**each annihilation produces  $10^4 M_{12}^{1/2} \nu_\tau$ 's**

# Neutrino scattering

$\nu_e \rightarrow \cancel{e^+} + \dots$      $e$  and  $\mu$  absorbed  $\rightarrow$

$\nu_\mu \rightarrow \cancel{\mu^+} + \dots$      $\nu_e$  and  $\nu_\mu$  absorbed\*

$\nu_\tau \rightarrow \tau^+ + \dots$

  $\nu_\tau + \dots$

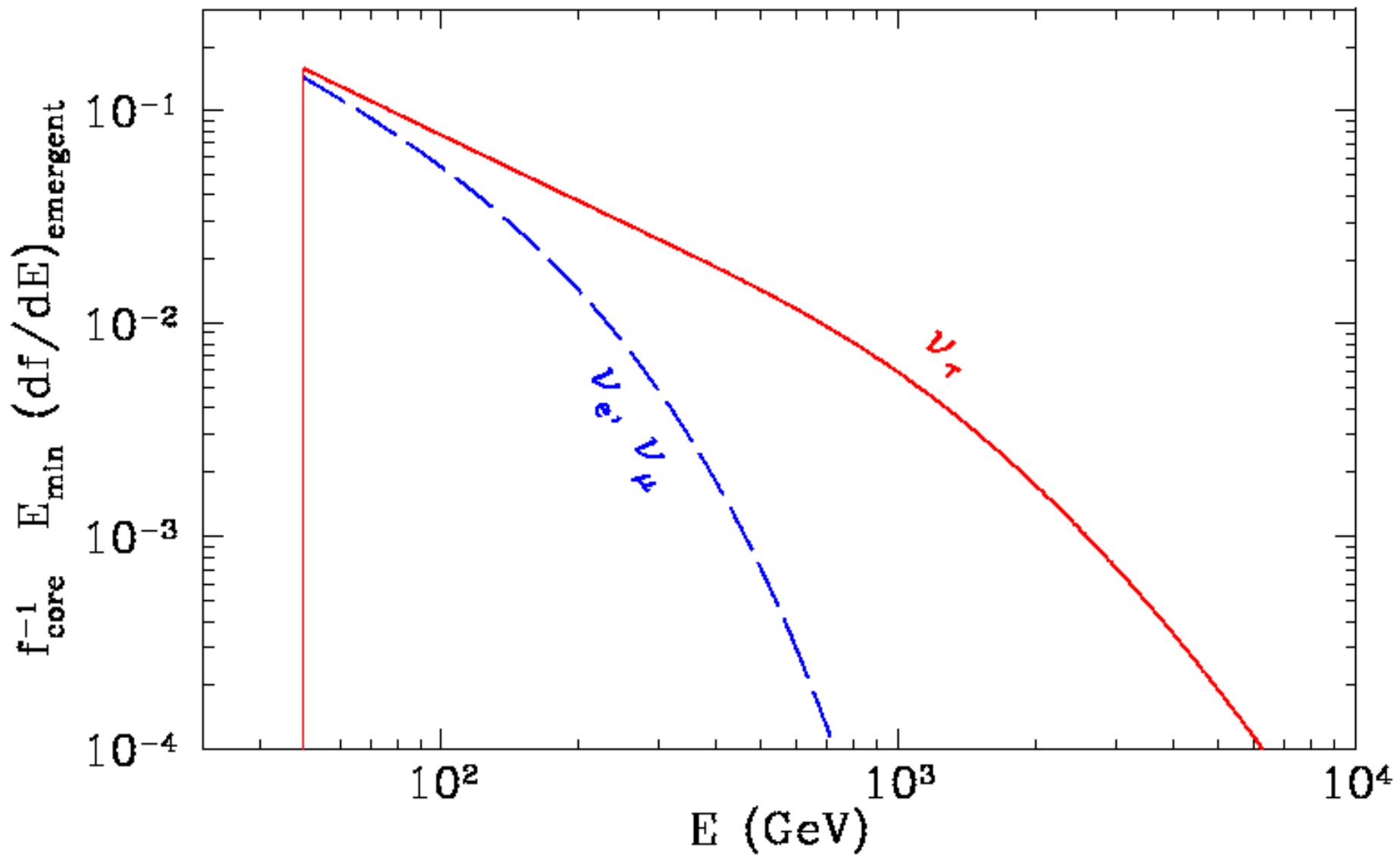
$\nu_\tau$  emerges as lognormal distribution centered at transparency energy (Halzen & Saltzberg)

**Transparency energy:**  $E_\kappa = 150$  GeV

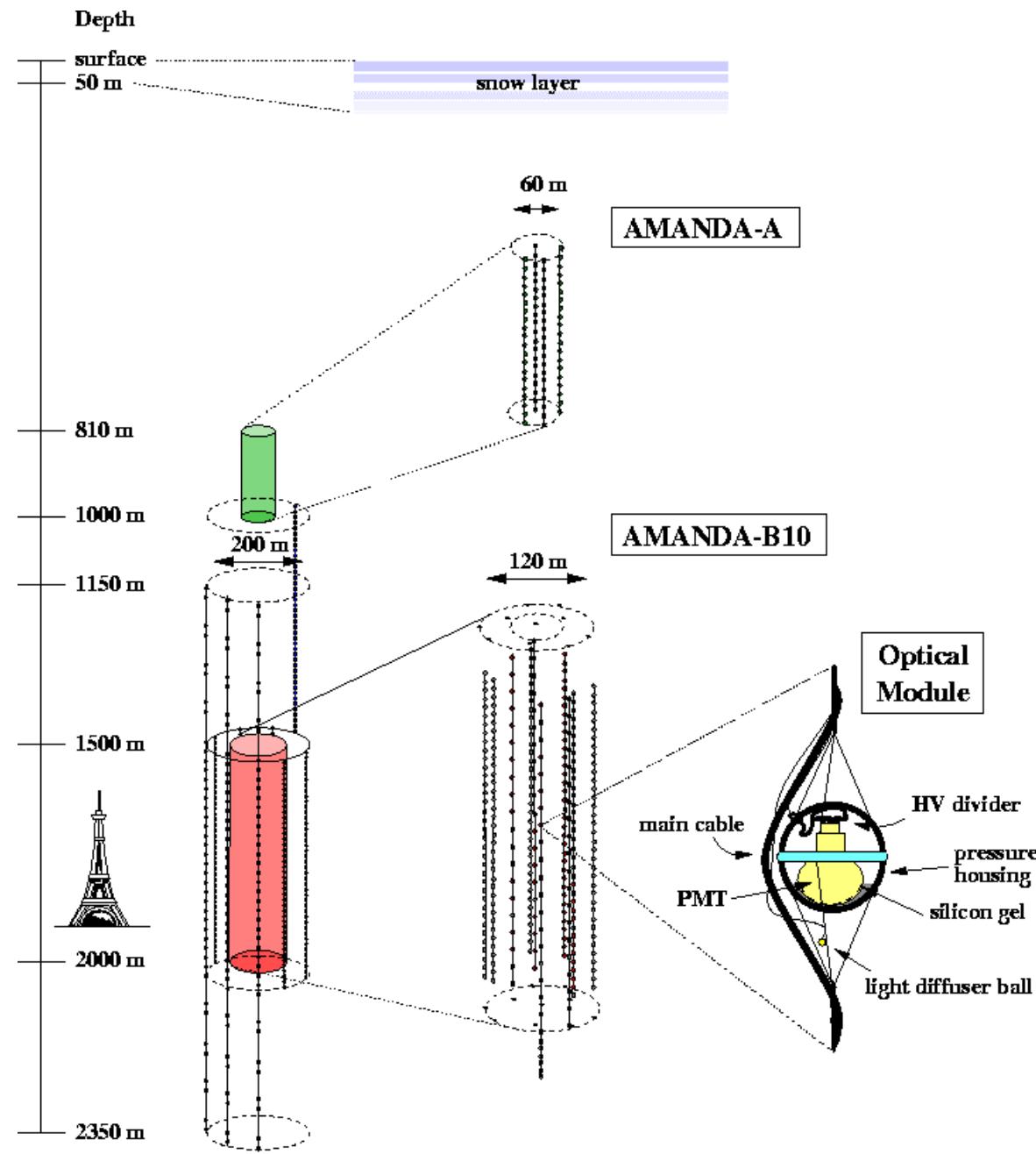
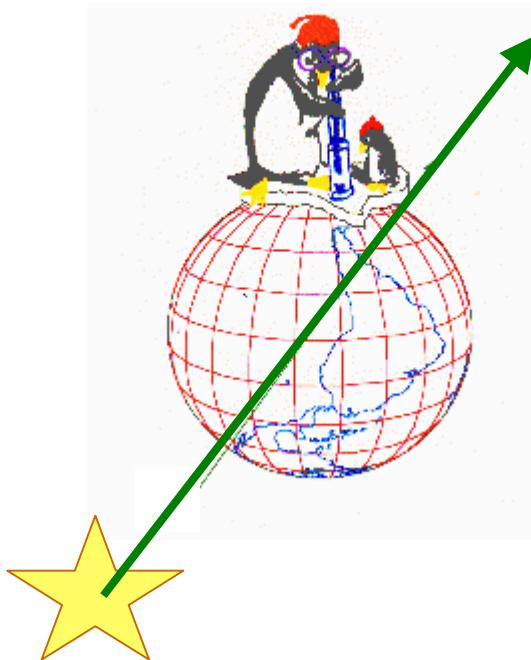
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\* except for  $\nu_e$  and  $\nu_\mu$  produced in 'last' interactions

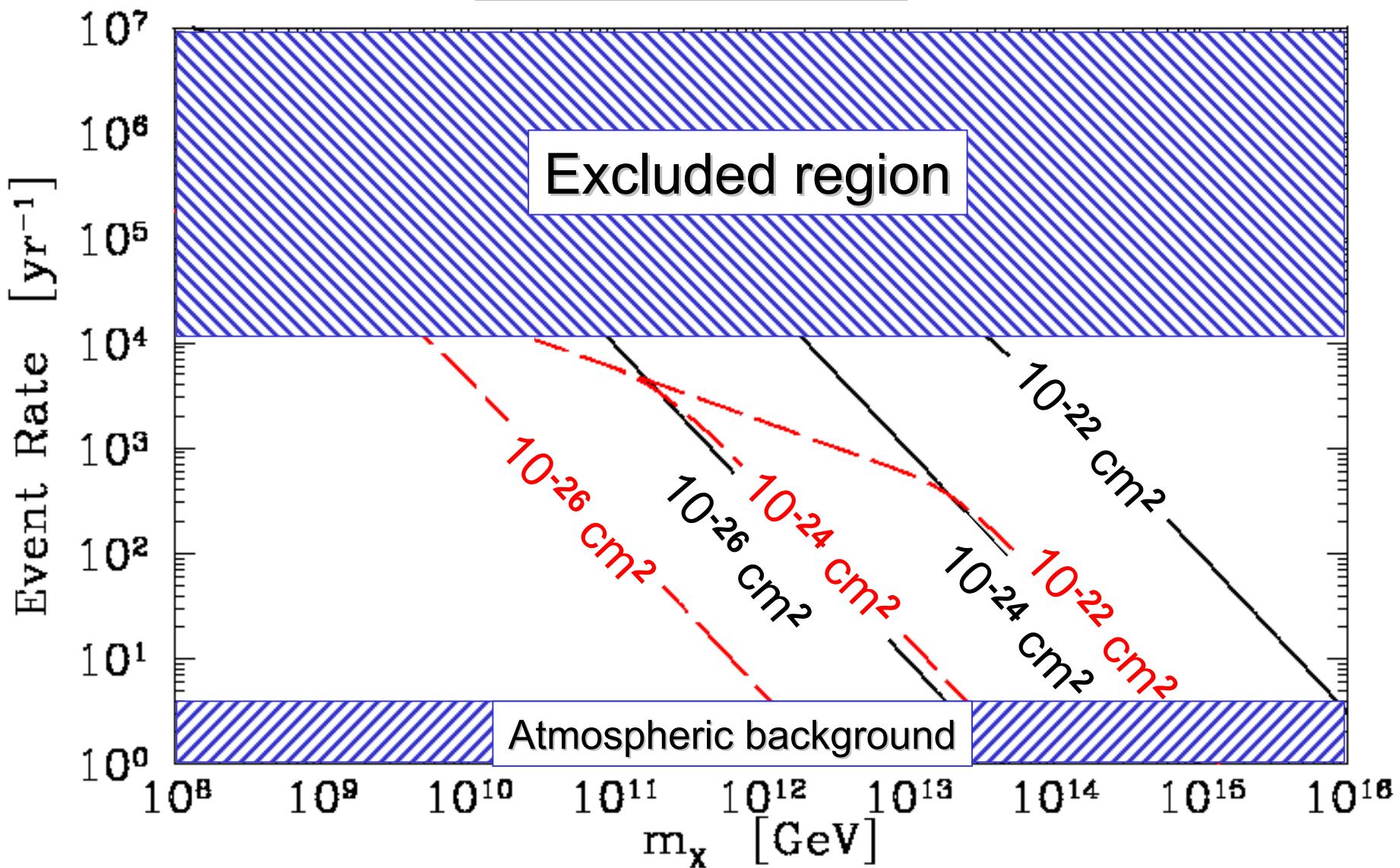
# Emergent spectrum



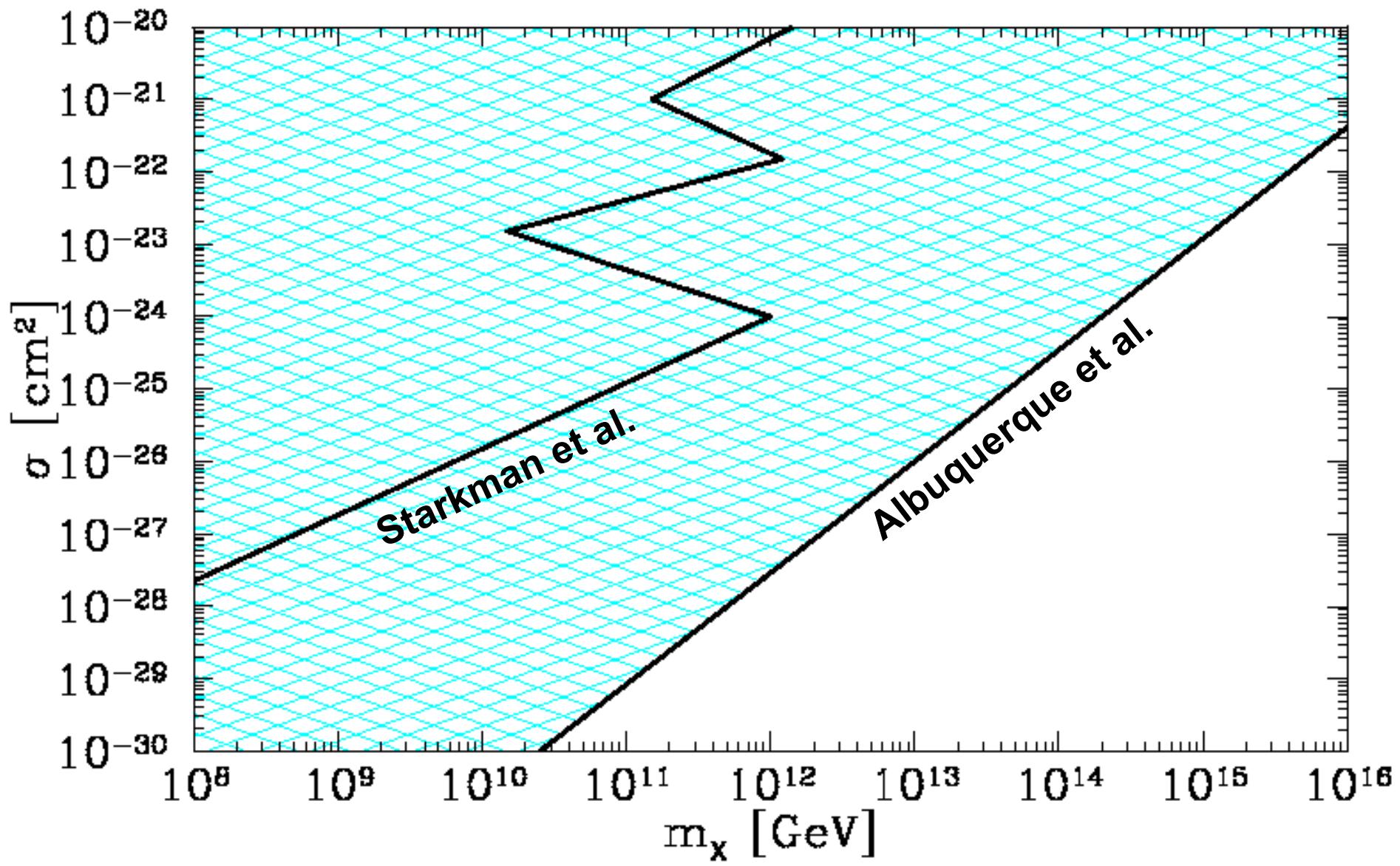
# **km<sup>3</sup>** **underice/ undersea neutrino telescopes**



# Event rate



# Excluded region



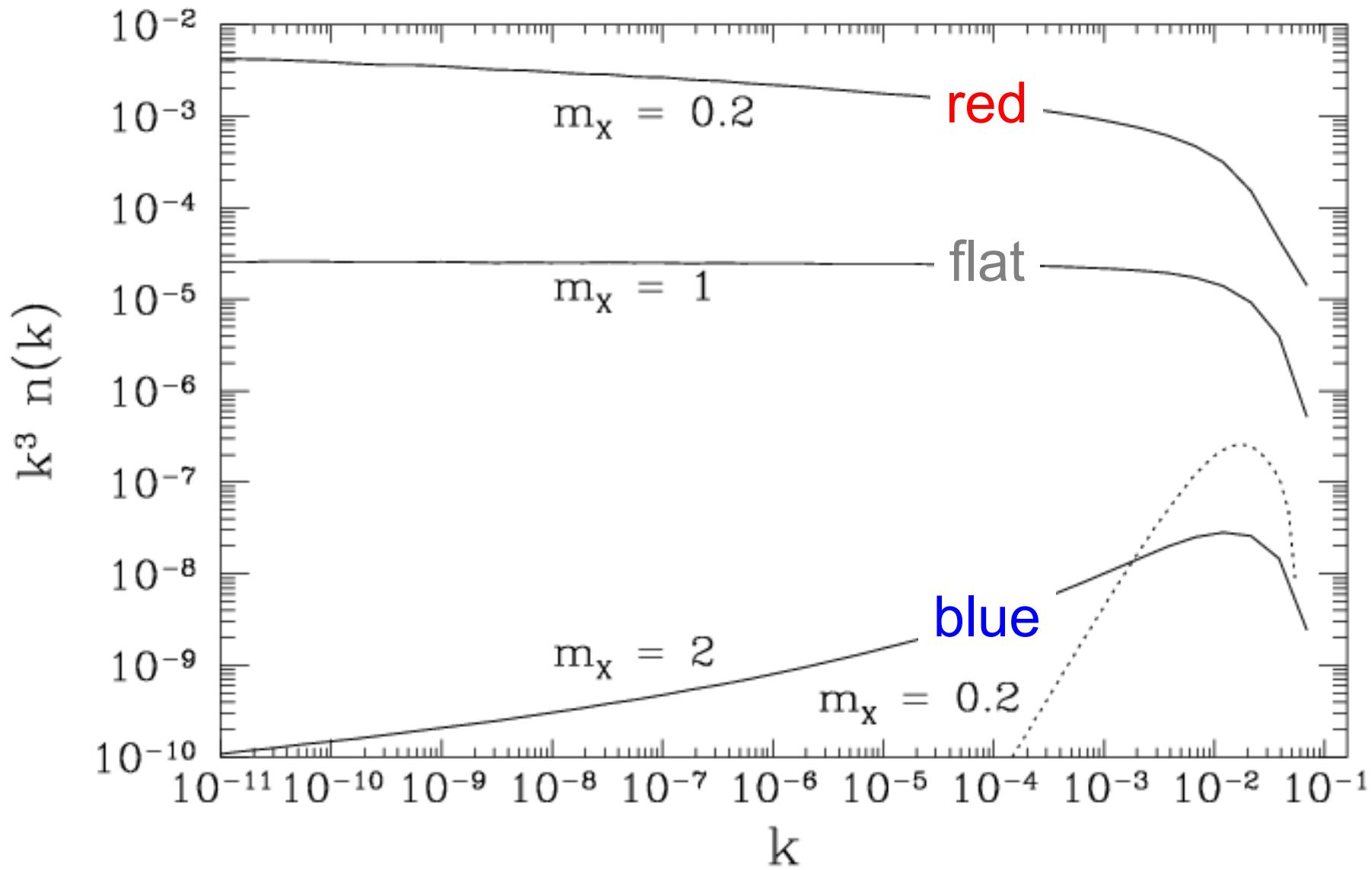
# Supermassive dark matter

- The “alarming phenomenon” may produce dark matter as well as seed perturbations.
- Dark matter may be **WIMPZILLAS!**
- WIMPZILLAS may be **undetectable!**
- But then again, they may be **detectable!**
  - direct
  - bulk
  - UHE cosmic rays
  - annihilation
    - galactic center
    - sun
  - other signals?

# Isocurvature modes

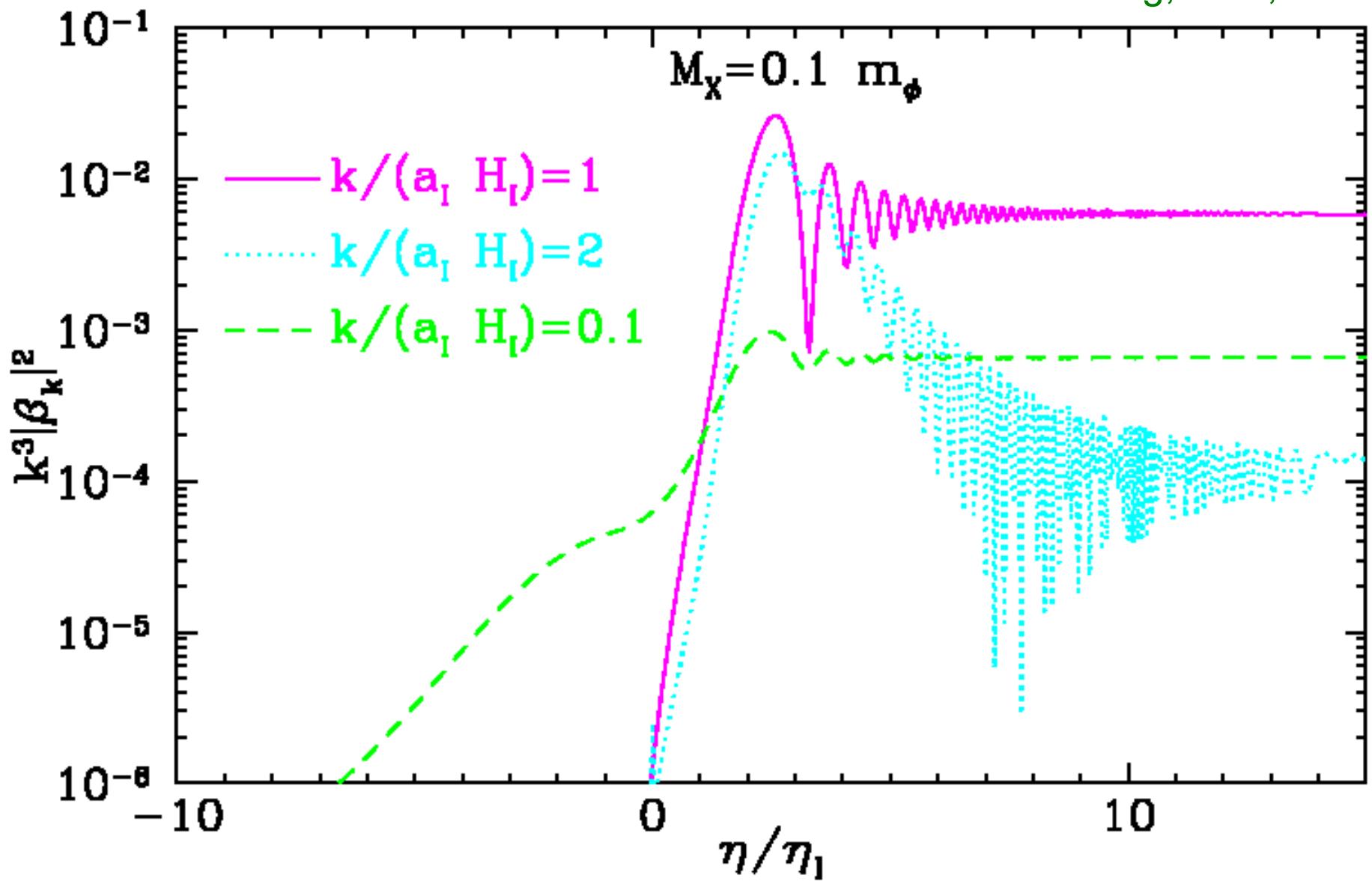
Kuzmin & Tkachev

Kolb, Riotto, Tkachev



# *H constant during inflation*

Chung, Kolb, Riotto

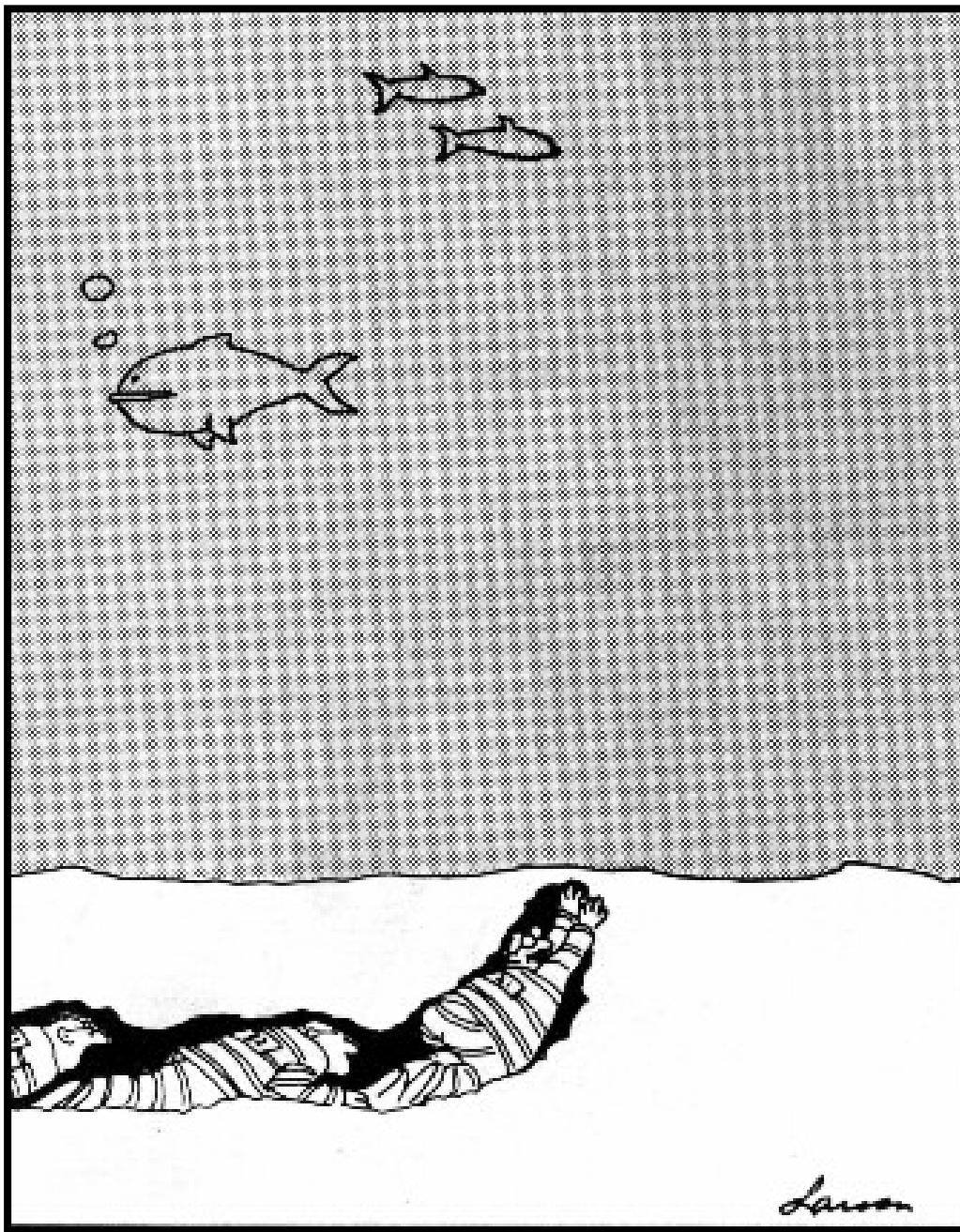


- Particle spectrum depends on  $\dot{H}$
- Scalar spectral index depends on  $\dot{H}$

# Gravitino production

Giudice, Riotto, Tkachev  
Linde, Kallosh, Kofman, Van Proeyen  
Nilles, Peloso, Sarbo  
Nilles, Olive, Peloso  
.....

**Lots of discussion at COSMO'99**



We're almost free, I just felt the first drops of rain

# Particle production

A field theory calculation:  
the result is almost always  
***infinite!***

<i>de Sitter (inflation)</i>	$a \propto e^{H_I t}$	<i>blows up at <math>t = \infty</math></i>
<i>matter, radiation</i>	$a \propto t^{2/3}, t^{1/2}$	<i>blows up at <math>t = 0</math></i>

**finite if start in inflation, end in  
matter/radiation**

## Solve wave equation

$$h_k''(\eta) + \omega_k^2(\eta) h_k(\eta) = 0$$

$$\omega_k^2(\eta) = k^2 + M_X^2 a^2(\eta)$$

$$h_k^0 = 1/\sqrt{2\omega_k^0} \quad h_k'^0 = -i\sqrt{\omega_k^0/2}$$

## Find Bogoliubov coefficient

$$|\beta_k|^2 = \frac{|h_k'|^2 + \omega_k^2 |h_k|^2 - \omega_k}{2\omega_k}$$

## Number density proportional to

$$\int_0^\infty \frac{dk}{2\pi^2} k^2 |\beta_k|^2$$